ERDC/CRREL SR-16-1

Cold Regions Research and Engineering Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

ERDC
INNOVATIVE SOLUTIONS for a safer, better world

Review of Ice-Control Methods at Lock 8, Welland Canal, Port Colborne, Ontario

Robert B. Haehnel

May 2016

ERDC/CRREL SR-16-1
May 2016

Review of Ice-Control Methods at Lock 8, Welland Canal, Port Colborne, Ontario

Robert B. Haehnel

U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

Final Report

Prepared for St. Lawrence Seaway Management Corporation
St. Catharines, Ontario

Under Cooperative Research and Development Agreement (CRADA) between ERDC-CRREL and the St. Lawrence Seaway Management Corporation
C-15-CRL-15, “Lock 8 Ice Management Study, Lake Erie Port Colborne, Ontario, Canada”

Abstract

This effort reviews the existing procedures and equipment used at Lock 8 on the Welland Ship Canal, Ontario, Canada, to control ice and to reduce the possibility of ice causing a shipping vessel to get stuck or jammed in the lock chamber. The lock uses several methods, including an air curtain to hold ice above the lock, bubblers and mechanical means to reduce the ice accumulation on the lock walls, and bubblers to flush ice from the gate recesses.

A review of all of these methods shows that mostly they have been effective, though some recommended modifications include reducing the air-curtain and bubblers nozzle size to make the flow across the manifolds more uniform. The only system that the St. Lawrence Seaway Management Corporation might consider replacing entirely is the blaster bubblers, which are unreliable and ineffective.

This report details recommended improvements to ice control at Lock 8, including a secondary air curtain below the existing air curtain, a manifold recess bubbler, and methods to further reduce the quantity of ice passing through the breakwater and bypassing ice down the weir channel. Further work is required to determine feasibility and the final design for each of these recommended changes.

Contents

Illustrations

Figures

Tables

Preface

This study was conducted for St. Lawrence Seaway Management Corporation (SLSMC) under a Cooperative Research and Development Agreement (CRADA) between the U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL), and SLSMC (C-15-CRL-15, “Lock 8 Ice Management Study, Lake Erie Port Colborne, Ontario, Canada.”) The technical monitor was Sukhjit Sadiora.

The work was performed by Dr. Robert Haehnel (Terrestrial and Cryospheric Sciences Branch, J. D. Horne, Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Loren Wehmeyer was Chief of the Research and Engineering Division of ERDC-CRREL. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

I would like to thank Glenn Rutherford, SLSMC; Joseph Rocks, CRREL; and Steven Daly, CRREL, for their thoughtful reviews of this report.

COL Bryan S. Green was Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms and Abbreviations

AFDD	Accumulated Freezing Degree-Days
CFM	Cubic Feet per Minute
CMM	Cubic Meters per Minute
CRADA	Cooperative Research and Development Agreement
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
ERDC	Engineer Research and Development Center
ID	Inside Diameter
SCFM	Standard Cubic Feet per Minute
SCMM	Standard Cubic Meters per Minute
SLSMC	St. Lawrence Seaway Management Corporation
USACE	U.S. Army Corps of Engineers
WSC	Welland Ship Canal

Unit Conversion Factors

Multiply	By	To Obtain
atmosphere (standard)	101.325	kilopascals
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
miles (U.S. statute)	1,609.347	meters
pounds (force) per square inch	6.894757	kilopascals

Executive Summary

The Welland Ship Canal (WSC) is 26 miles (42 km) long and connects Lake Erie to Lake Ontario through eight locks with a total fall of about 300 ft (100 m), proceeding in the direction of Erie to Ontario. Lock 8 is located in Port Colborne, Ontario, Canada, and is the first lock from Lake Erie. It is a control lock that compensates for variations in the lake level and has a relatively small lift of 2–5.5 ft (0.6–1.7 m).

During winter operations, vessels can become jammed in the lock as ice carried in with the vessel becomes “pinched” between the lock wall and the vessel; there are no reported problems of ice grounding out between the bottom of a vessel and the channel or lock bottom. Ice conditions can increase lockage time to an hour or more; and in extreme cases, a vessel can be lodged in the lock for as many as 4 days, though it is much more common for the time needed to free a vessel to last a day or less. This report reviews the current ice-management practices and equipment used at Lock 8 and provides recommendations for possible ways to improve ice management at the locks.

Current methods include monitoring weather conditions and implementing ice forecasting methods to determine when ice-control measures should be implemented, using bubbler screens or air curtains to reduce the amount of ice entering the lock, removing ice from lock walls and approaches by using bubblers and mechanical methods (e.g., scraping the lock wall with tugs or excavation equipment), and flushing ice from miter gate recesses and the lock chamber. Also, the presence of a breakwater between Lake Erie and the WSC helps to reduce ice entering the shipping channel and reaching the lock.

Most of these methods appear to be effective. What follows is a list of observations and recommendations that should improve ice management at Lock 8.

1. A review of the performance of the blaster bubblers used to clear ice from the miter gate recesses shows that this may not be as effective as herding the ice out of the recess with a removable point-source bubbler.
2. A design for a manifold recess bubbler is provided in Section 4.3 that may prove to be much more effective and reliable for clearing the gate recess of ice than the blaster or point-source bubblers.

3. A review of the existing and planned replacement air curtain (Table 1) revealed that the existing nozzles are too large to provide uniform airflow across the length of the air-curtain manifold. From this review and based on the design guidelines of the U.S. Army Corps of Engineers (USACE 2006), I recommend that the replacement air curtain use nozzles that are 0.35 in. (8.9 mm) in diameter (S drill size) with a spacing of 8 ft (2.4 m). The new air curtain would require a compressor capacity of 2400 SCFM* (68 SCMM†). I estimate that the new curtain would have a 30% higher capacity to hold back ice than the existing air curtain.
4. Reducing the nozzle diameter to 0.316 in. (8.0 mm or a number 29 drill) for the bubblers under Bridge 19 would improve uniformity in the airflow rate across the length of the bubbler manifold. When this bubbler is rehabbed, I recommend replacing the existing nozzles with this smaller nozzle size.
5. Owing to the effectiveness of the bubbler system under Bridge 19 at keeping ice off the approach wall under the bridge, it is worth considering this same approach under Bridge 19A, provided the above recommendations (e.g., reduced nozzle diameter) for the system under Bridge 19 be used at 19A as well. I would expect that such a system would perform on par with the current system under Bridge 19; however, I recommend measuring the water temperature at the bottom of the channel under Bridge 19A for at least one winter to determine if there are ample warm water reserves for a bubbler to effectively operate at that site as well.
6. To reduce the likelihood of the bubbler supply lines becoming frozen during the winter months, I recommend installing check valves in the lines as discussed in Section 4.2.
7. Adding a second air curtain downstream of the existing air curtain may help reduce the ice entering the lock and thereby reduce the chances of a vessel becoming jammed in the lock chamber. As detailed in Section 4.1, this second air curtain would be operated intermittently to hold in the lock approach ice that passes with the vessel through the first air curtain. Then, once the vessel has been locked, the ice held by this secondary curtain can be released and flushed through the lock using existing ice lockage procedures.
8. To further reduce the quantity of ice in the upper approach, it is worth considering the methods discussed in Section 4.5 for reducing the ice flow through the existing breakwater opening.

---

* Standard cubic feet per minute
† Standard cubic meters per minute

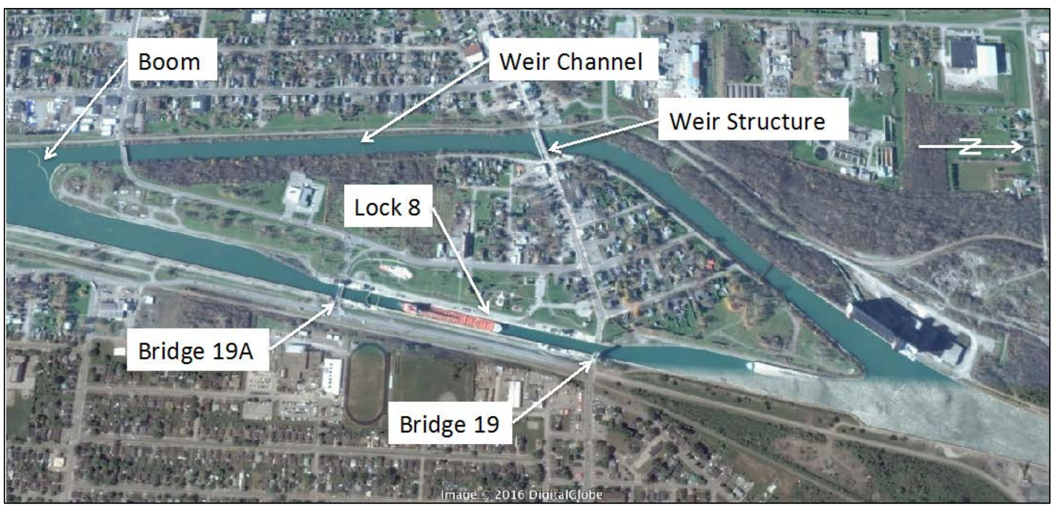
9. This report reviewed diverting ice around the lock by passing it through the weir channel and weir structure (Section 4.6) as a possible method to reduce ice in the upper approach. Though the preliminary analysis performed in the present effort shows that this approach may be feasible, further work is required to refine the methods and structural design needed to implement this concept.

1 Introduction

1.1 Background

The Welland Ship Canal (WSC) is 26 miles (42 km) long and connects Lake Erie to Lake Ontario through eight locks for a total fall of about 300 ft (100 m), proceeding in the direction of Erie to Ontario. Lock 8 is located in Port Colborne, Ontario, Canada, and is the first lock from Lake Erie (Figure 1). It is a control lock that compensates for variations in the lake level and has a relatively small lift. The maximum head difference across the lock is about 5.5 ft (1.7 m), and the minimum head difference is a little less than 2 ft (0.6 m).

Figure 1. The layout of Lock 8 and the surrounding structures, Port Colborne, Ontario. Flow in the shipping channel is from left to right.



The lock width is 80 ft (24.4 m), and the maximum vessel beam is 78.7 ft (23.98 m)*, leaving a 0.65 ft (0.15 m) of clearance on either side of the vessel. Only the newest vessels are that wide; the typical vessel is 730 ft (222.5 m) long with a 78 ft (23.8 m) beam. Oversize vessels are as long as 740 ft (225.5 m). The width of the channel narrows in the lock approach from 210 ft (64 m) at the bullnose to 80 ft (24.4 m) at the lock entrance. The guaranteed channel depth is 30 ft (9.1 m); the maximum allowable draft of the vessels is 26.6 ft (8.1 m).

* Glenn Rutherford. Personal communication. 24 September 2015. St. Catharines, ON: St. Lawrence Seaway Management Corporation.

The flow out of Lake Erie to the WSC is divided between Lock 8 (east channel) and the weir channel on the west (Figure 1). The flow through the weir channel is regulated by the weir structure under the northern bridge over the weir canal. This has a system of ten 15 ft (4.57 m) wide (opening width) taintor valves that run the full width of the channel. The purpose of the weir channel and weir structure is to control the flow from Lake Erie to maintain the pond elevation between Lock 8 and Lock 7. The bulk of the water flowing in the WSC passes through the weir channel. Only about 1% of the daily flow passes through the lock. Currently, a boom at the upstream end of the weir channel prevents ice and debris from passing down the weir channel.

The WSC is closed to shipping from 31 December to 20 March annually. Though it is not operated through the winter, Lock 8 can experience ice conditions in December before it closes and again after it opens in March until as late as May. According to lock operations personnel, ice continues to flow into the entrance from Lake Erie to the WSC until the ice boom on the Niagara River is removed, drawing ice down the Niagara River and away from Port Colborne. Some years, the Niagara River boom is not removed until as late as May.

During winter operations, vessels can become jammed in the lock as ice carried in with the vessel becomes pinched between the lock wall and vessel; there are no reported problems of ice grounding out between the bottom of a vessel and the channel or lock bottom. In extreme cases, a vessel can be lodged in the lock for as many as 4 days though it is much more common for the time needed to free a vessel to last a day or less. Yet, ice conditions can generally slow the lockage process to an hour or more.

1.2 Objectives

CRREL was asked by the St. Lawrence Seaway Management Corporation (SLSMC) to review the current ice-management practices and equipment used at Lock 8 and to provide recommendations for possible ways to improve ice management at the lock. The objective of this study is to find ways to reduce the likelihood of vessels getting jammed in the lock during lock operations and reduce vessel lockage time during winter operations. This was accomplished through a site visit, discussions with lock operations personnel, review of design drawings of the lock and ice control systems at the lock, and analysis of the expected performance of the system components.

2 Current Ice-Management Practices

A vessel becomes jammed in the lock due to the clearance between the side of the vessel and lock wall being filled with ice, either ice that has become frozen on the lock wall or is in the lock chamber or ice that is carried with the vessel into the chamber and is pinched between the lock wall and vessel as it enters the lock. Therefore the main objectives of ice-management methods are

1. to reduce build-up of ice along the lock walls and gate recesses,
2. to prevent ice being carried into the lock chamber with the vessel, and
3. to remove loose ice in the lock chamber before a vessel enters.

What follows is a summary of the methods currently used to manage ice in the and around Lock 8.

2.1 General methods

2.1.1 Ice forecasting

Personnel at Lock 8 take advantage of the St. Lawrence Seaway Management Corporation (SLSMC) ice forecasting system to determine when to start implementing ice-management measures and to rent compressors for operations of the several bubbler systems used at the lock. SLSMC personnel report that ice problems at Lock 8 usually start when accumulated freezing degree-days (AFDD) reach 30–50 degree days (°C). Use of the ice forecasting system to prepare for ice formation in the WSC is effective and should continue.

2.1.2 Removal of ice from the lock wall

A tug or a tug fitted with a bow-mounted scraper is often used to remove ice from the lock walls. In extreme icing cases, backhoe equipment may also be used to scrap ice off walls. Bubblers have been installed on the lower approach wall under Bridge 19 to keep the wall ice-free. In this area, the channel is the same width as the lock chamber; and the shadow of the bridge allows the wall to stay cold, and ice can build up on the wall in that region. The bubbler system brings warmer water from the channel bottom to the surface, helping to prevent formation of an ice collar on the wall. This bubbler is operated continuously through the winter months.

2.1.3 Flushing ice from the miter gate recesses

There are four miter gates in the lock: two main gates and two auxiliary gates. All of these are hydraulically operated. The main gates are fitted with "blaster" bubbler systems. A 185 SCFM* (7.2 SCMM†) compressor (flow at standard conditions of 1 atm [101.325 kPa] and 20°C, the rated flow of the compressor) is used to store air at 135 psi (930 kPa) in a 1000 gal. (3.78 m^3) tank. The air is released from the tank via a solenoid valve through a 1.25 in. (31.8 mm) inside diameter (ID) pipe with the open end positioned in the gate quoin (hinge or pivot area); there is no nozzle on the pipe end. The air dumped from the tank is intended to "blast" the ice out of the quoin area. However, SLSMC personnel report that this bubbler system is not very effective and that the system breaks a lot. Therefore, the main method used to flush ice from the gate recess is removable point-source bubblers lowered in the quoin area. These bubblers are simply a 0.75 in. (19 mm) air hose attached to a 135 psi (930 kPa), 185 SCFM (7.2 SCMM) compressor. Like the blaster bubbler, there is no nozzle at the end of the hose. The hose can be lowered from the lock wall and moved around to flush ice from the gate recess or from other problem areas. Note that the main gates are currently out of service and are scheduled to be rehabbed during the winter of 2015–16. The secondary gates are currently being used. The removable point-source bubblers are the only current means of flushing the gate recess of these secondary gates.

2.1.4 Breakwater

Though the primary intent of the breakwater between Lake Erie and WSC (Figure 2) is to reduce wave action from Lake Erie impacting operations in the harbor and docks at the entrance to WSC, it also limits to some extent the amount of ice that passes into the WSC. There are two openings in the breakwater. On the west end, the breakwater terminates about 1100 ft (330 m) from shore. However, ship traffic passes through the central opening (Figure 2), which is about 614 ft (187 m) wide. As previously mentioned, SLSMC personnel report that when the ice boom in the mouth of the Niagara River is removed from Lake Erie, the ice is drawn toward the Niagara River, and less ice enters the canal. Sometimes the boom is not removed until as late as May, and ice passing from Lake Erie through the breakwater can causes problems at Lock 8 through April. It is unclear

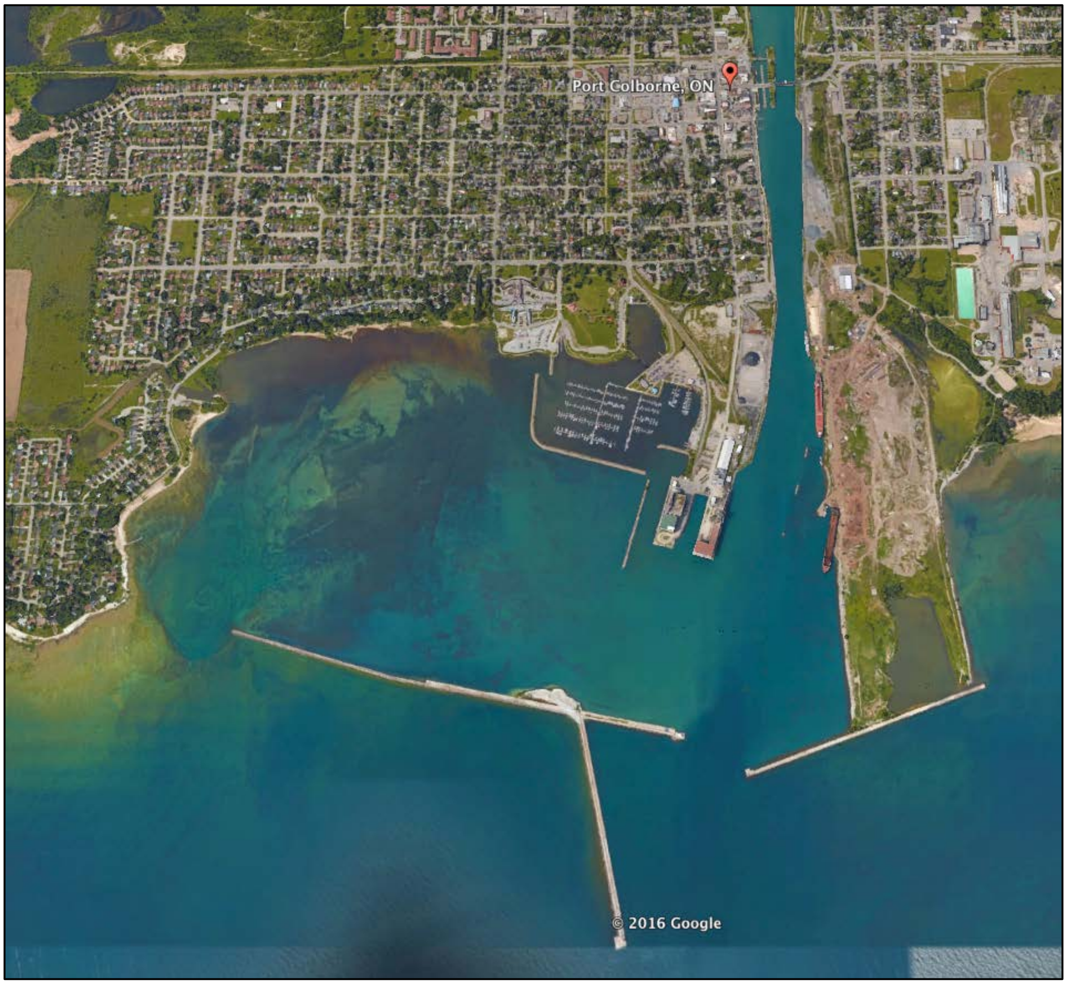
---

* Standard cubic feet per minute

† Standard cubic meters per minute

what the stability of the ice is in the bay north of the breakwater. If a stable ice cover forms in most of the bay west of the shipping channel, one can expect that little to no ice enters through the west opening. If this is the case, typically most of the ice that comes from Lake Erie enters through the opening in the breakwater for the shipping channel.

Figure 2. The entrance to Welland Ship Canal from Lake Erie. The breakwater is seen at the *bottom* of the image (with a groin extending into Lake Erie) and has openings on the west side and a central opening for ship traffic.



2.2 Northbound traffic

The following methods and equipment are more specifically for supporting passage of northbound traffic.

2.2.1 Air curtain located at the bullnose

An air curtain, or bubbler screen, at the bullnose is used to hold ice there. The objective is to keep the fore bay, or upper lock approach, ice-free as shown in Figure 3. In addition to holding the ice above the lock approach when there are no vessels present, the air curtain also helps to "sweep" the ice off the bow and sides of the vessel as it passes through the curtain. Ships approach the screen on the east wall and pass through the air curtain. Once through the air curtain, they use the port thrusters to try to clear ice off the port side and move toward the west wall to tie up and wait or align for approach to the lock. Depending on the amount of ice in the upper approach, the air curtain does not always clean all of the ice off of the hull of the vessel. This bubbler is operated continuously through the winter season to hold the ice at or above the bullnose when traffic is not passing.

Figure 3. View looking north on the upper approach to Lock 8. A bubbler screen holds ice (*foreground*) from entering the approach. The effectiveness of the bubbler is demonstrated by the ice-free approach (*top* of picture). (Photo courtesy of SLSMC.)

The current bubbler was installed in 1980 and is galvanized pipe. It is due to be replaced with stainless steel pipe in January 2016. SLSMC personnel report that currently the bubbler plumes near the east wall are weak, but that has not always been the case. Corrosion of the system can increase the roughness of the pipe and cause either partial blocking of some nozzles or enlarging of other nozzles that results in less air reaching or being let out of the far end.

2.2.2 Ice flushing

When too much loose ice is in the lock chamber, an ice lockage (or flushing) is required to clear the ice from the chamber before a vessel is locked through. Through the winter, a tug is available to move ice in the approaches and to help with ice flushing. The procedures for locking ice are outlined in the *Lock Operations Manual* (SLSMC 2015) Section L3.2: "Ice flushing procedure." In short, the lower gates are closed and the emptying (lower) valves are opened to draw ice into the lock. As much ice as is possible is drawn into the lock, yet it is important to limit the amount of ice drawn in so that it does not interfere with the closing of the upper gates. Once sufficient ice is drawn into the chamber, the lower valves are closed; and then upper miter gates are closed. The lower miter gates are then opened; once they are fully opened, the upper valves are opened to flush the ice from the chamber. This procedure may need to be repeated to handle all of the ice that needs to be cleared from the upper approach.

2.3 Southbound traffic

Some of the above-discussed procedures are used to handle ice for southbound traffic, also (e.g., ice flushing). Yet, a feature in the lock that is reported as being particularly helpful for southbound traffic is the bubbler under Bridge 19; Bridge 19 passes over the lower approach to Lock 8 (Figure 1). As a vessel passes by Bridge 19, these bubblers help to clean ice off the sides of the vessel as it moves into the lock. Because these bubblers do not extend across the width of the lower approach, they are not effective at removing ice that may be pushed in front of the vessel, only the ice that clings along the side.

3 Evaluation of Current Procedures

Section 2 provides an overview of the procedures used at Lock 8 to control ice. To better assess the effectiveness of the methods used and areas where the methods might be improved, in this section, I provide a detailed review of most of the current procedures.

3.1 Removing ice from lock walls

Owing to the abrasive condition these walls are subjected to and the fact that there is already minimal clearance between the vessel and the lock walls, I do not advise adding heater panels to the lock wall. Panels would likely not stand up to the rigors of the lock environment and would encroach on the limited clearance. Continued removal of ice from the lock walls by using mechanical means is still a good option. Yet, successful use of bubblers along the lower lock approach at Bridge 19 demonstrates that there is likely adequate warm water at depth that can be used to prevent ice formation on the lock walls. If ice accumulation on the lock walls in the chamber or upper approach proves to be a persistent problem, SLSMC may want to consider the addition of bubbler systems along the chamber walls or in the upper approach under Bridge 19A. However, before pursuing this line of action, I recommend that the water temperature at depth be monitored through the operational months of the lock to verify that there is an ample supply of warm water at the bottom of the lock that can be used to keep the walls free of ice. Provided that there is ample warm water in the chamber or upper approach, I would expect that a bubbler system patterned after what is used under Bridge 19 would perform on par with that system.

3.2 Point-source bubblers for flushing the gate recesses

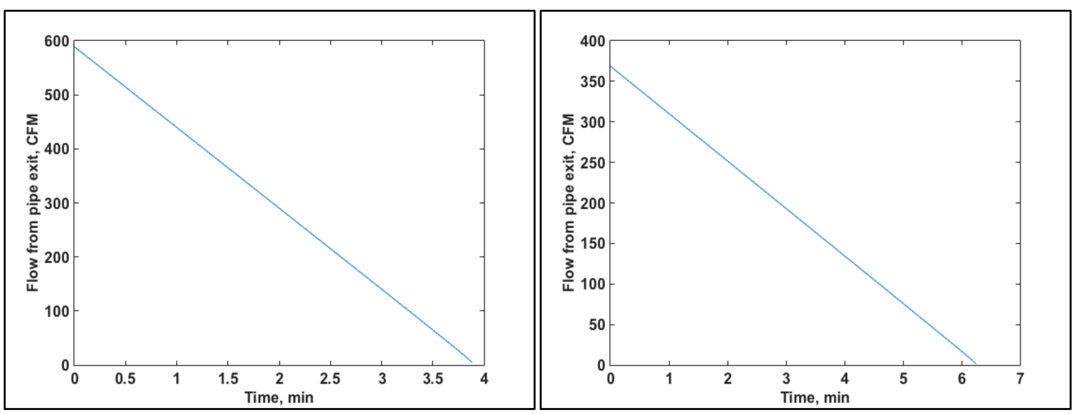
I computed the performance of the blast bubblers to determine the approximate flow out the end of the pipe as a function of time. Figure 4 shows the result of this analysis. As shown in Figure 4, when the solenoid valve is initially opened, a rush of air will exit the tank. Over time, the flow will drop as the pressure difference between the air in the tank and the pressure at the pipe exit reduces and approaches the pressure at the exit of the pipe. The flow out of the near side and far side pipes differ with the initial flow out of the near side bubbler starting at just under 600 CFM* (17

* Cubic feet per minute

CMM*), and the far side bubbler releases about 360 CFM (10 CMM) initially. The lower flow out of the far side bubbler is due to the frictional losses associated with the longer supply line; the supply line feeding the far side bubbler is about 172 ft (52 m) while the supply line on the near side is about 60 ft (34 m).

If the 185 SCFM (7.2 SCMM) compressor that is used to fill the tank for the blaster bubbler were instead directly used to feed the bubbler line (i.e., bypassing the storage tank), the approximate volumetric flow rate exiting the bubbler line would be about 89 CFM (2.5 CMM), owing to the pressure and temperature conditions at the pipe exit. A question of interest is how long the blaster bubbler will provide a flow above the 89 CFM that the compressor can provide on its own. On the near side, the flow is maintained above 89 CFM for about 3–3.5 min while, on the far side, the bubbler operates above the compressor flow rate for about 4.5 min.

Figure 4. The computed flow out of the pipe exit of the blaster bubbler for (*a*) near side and (*b*) far side bubblers. The depth of submergence is 32 ft (9.8 m).



(a) (b)

It is questionable whether the elevated flow provided by the blaster bubbler is sustained for enough time to flush the ice out from the recess or whether operating the bubbler at a lower flow rate for a longer period would be more effective. Presently, the removable point-source bubbler operates the same as bypassing the blaster bubbler storage tank as it uses the same size compressor (135 psi [930 kPa], 185 SCFM [7.2 SCMM]). Kobus (1968) documented the bubbler plume structure created by point-source and linear (manifold) bubblers. The insight gained in that work helps in making a comparison between the performance of the blaster

* Cubic meters per minute

bubbler and the removable point-source bubbler. In particular, Kobus (1968) studied the effect of bubbler depth, nozzle diameter, and bubbler flow rate on the plume diameter and on the upward water velocity induced by the bubbler plume. Kobus (1968) showed that the upward velocity is a function of bubbler depth, radial distance from the plume centerline, and bubble flow rate and that the nozzle diameter has a negligible effect on the upward velocity. Note that the work of Kobus (1968) studied a point-source bubbler in the middle of a body of water, not near a wall or in a corner such as in this case with a bubbler acting in a gate quoin. Still, use of the work of Kobus (1968) provides a reasonable basis to compare the performance of these two bubblers even if the geometry is not identical.

Kobus (1968) showed that the upward velocity profile is well approximated by a Gaussian distribution such that

$$\frac{u(r,x)}{u_{CL}(x)} = e^{-\frac{r^2}{2\sigma^2}} \tag{1}$$

where

- x = the vertical distance above the nozzle;
- r = the radial distance from the plume centerline;
- u = the water velocity as a function of r and x;
- u_{CL} = the vertical water velocity at the centerline of the plume;
- c = an empirically determined spread rate (for a solitary bubbler, or point-source bubbler, Kobus 1968 determined that $c = 0.0721Q^{0.15}$ with Q, the air flow rate exiting the bubbler line, having units of CMM);
- σ = $c(x + x_o)$ = the standard deviation, or “spread” parameter; and
- x_o = the vertical offset below the nozzle to the “analytical origin” of the plume, empirically determined as $x_o = 0.8$ m by Kobus (1968).

The plume centerline velocity is determined from the analytic expression (Kobus 1968)

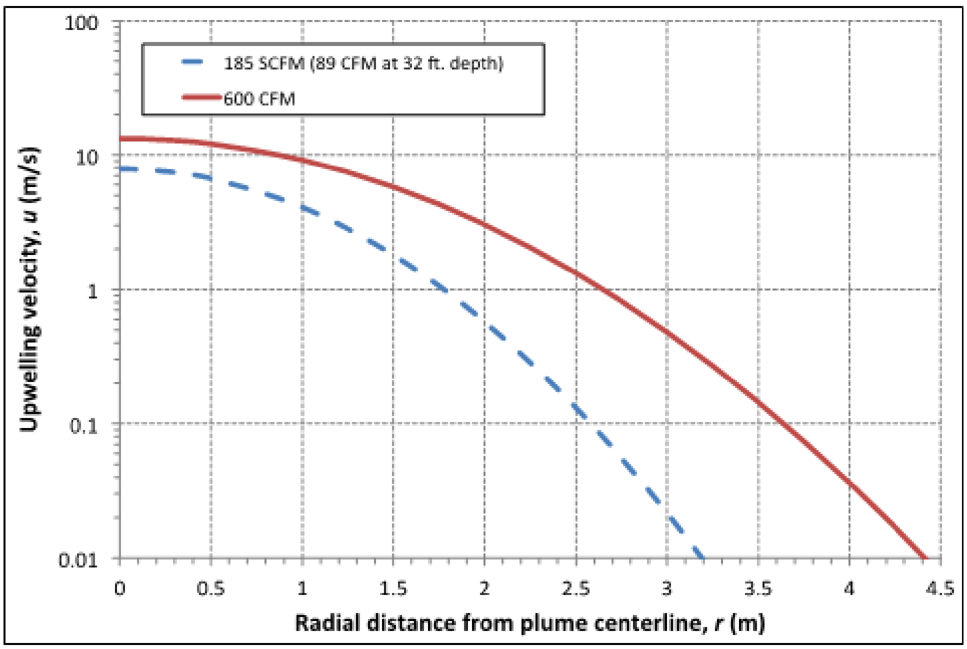
$$u_{CL} = \frac{1}{c(x+x_o)}\sqrt{\ln\left(1-\frac{x}{h^*}\right)\frac{-P_{atm}Q}{\pi\rho_w\overline{u_b}}} \tag{2}$$

where

P_{atm} = atmospheric pressure,
ρ_w = water density,
$\overline{u_b}$ = the average bubble rise velocity (Kobus 1968 found $\overline{u_b} = 0.992Q^{0.15}$ with Q in CMM),
h = the submergence depth of nozzle,
g = a gravitational constant, and
h^* = $h + P_{atm}/g\rho_w$.

Using Equation (1) and Equation (2), I can estimate the size and intensity (vertical water velocity, or upwelling velocity) of the bubbler plume near the surface and can compare the performance of the blaster bubbler and a point-source bubbler submerged to the same depth. Figure 5 provides the results of this analysis.

Figure 5. Computed near-surface upward velocity of a point-source bubbler plume submerged to a depth 32 ft (9.8 m).



Kobus (1968) does not provide data or other information on the outward flow velocity induced at the surface by a bubbler plume, which would be the most beneficial information for determining the ability of the plume to move ice or debris floating on the water surface. However, I assume that the upwelling velocity near the surface is proportional to the outward surface velocity and can be used to give a relative measure of the plume size (radius) and how vigorous the surface flow is some distance from the plume center. Therefore, in this analysis, I use $x = h$ in Equation (1) and

Equation (2) to get an estimate of the near-surface flow structure. In Figure 5, I compare the upwelling velocity near the surface for two point-source bubblers submerged to a depth of 32 ft (9.8 m). The flow rate of 600 CFM (17 CMM) is used to illustrate the performance of the blast bubbler at start-up while the lesser flow rate is associated with the removable point-source bubbler that is driven by a 185 SCFM (7.2 SCMM) compressor. As noted previously, the flow rate from the end of the removable point-source bubbler hose is 89 CFM (2.5 CMM) at a water depth of 32 ft (9.8 m), owing to the hydrostatic head at depth compressing the air, thereby reducing the volumetric flow rate though not the mass flow rate. Using the corrected flow rate of 89 CFM allows direct comparison to the 600 CFM flow from the blast bubbler exit. I make a comparison to only the near side blast bubbler in this analysis.

Note that the centerline velocity for the blast bubbler is initially about 70% higher than the removable point-source bubbler. However, the plume intensity for the blast bubbler declines over time (e.g., Figure 4); and as mentioned previously, after about 3–3.5 minutes, the flow has dropped to about the same level (89 CFM [2.5 CMM]) as that coming from the removable point-source bubbler. Still, even though the blast bubbler is more vigorous at the centerline during this time, it is the radius of the plume that provides a better indication of the ability of the bubbler to move ice out of the recess. According to Drawing C-8406 (A. W. Robertson and Co. 1933)*, the gate recesses at Lock 8 appear to be about 48 ft 2.5 in. (14.7 m) long. Figure 5 shows that at a distance of about 14.4 ft (4.4 m) from the center of the blast bubbler plume, the near-surface upwelling velocity has dropped to 0.033 ft/s (10 mm/s), which may be too low to effectively move the ice; of course that radius will decline over time as the flow decreases. Considering that the recess is over three times longer than that distance, the blaster bubbler may not be very effective at flushing the ice out of the entire length of the recess; and the 3–4 minute period that the flow is above that of the removable point-source bubbler may not give it much of an advantage.

The removable point-source bubbler flushing continuously with 185 SCFM (7.2 SCMM) can maintain a velocity of 0.033ft/s (10 mm/s) or higher out to about 10.5 ft (3.2 m), indicating that the point-source bubbler, if held stationary in the quoin area, is somewhat less effective at clearing the re-

* All drawings were provided by SLSMC.

cess. Yet, from a practical point of view, the removable point-source bubbler may be more effective than the blaster bubblers that have the nozzle permanently mounted in the quoin. Holding the gate partially closed, the ice can be herded out of the recess by slowly moving the removable point-source bubbler from the quoin out to the end of the gate. I am not sure if this is the current procedure used to flush the recesses with the removable bubbler or if these bubblers are just placed in the quoins to clear the recess of ice. Yet, if the ice is not herded out as described, this method should be considered going forward. Section 4.3 also discusses an alternative to point-source bubblers for clearing the recess of ice.

3.3 Breakwater

The breakwater is likely effective at significantly reducing the amount of ice that enters WSC. Yet, the opening is still large enough that ice continues to pass through the wall and can make its way to the lock. It may be possible to further reduce the amount of ice passing through the breakwater by placing temporary structures at the opening to reduce the opening width or to even close the opening when ship traffic is not passing through the wall. Section 4.6 discusses such measures further.

3.4 Air curtain located at the bullnose

I reviewed the current air-curtain (bubbler) design using the computer program BUB300 (USACE 2006). Detail E of Drawing C-8404-2 (Transport Canada 1980b) provided by SLSMC shows that the nozzle diameter for the existing air curtain is 0.236 in. (6 mm). The nozzle spacing is 3 ft (0.91 m) on a 4 in. (10.2 cm) ID manifold pipe. Drawing C-8404-1 (Transport Canada 1980a) shows the manifold length is 244.6 ft (74.540 m). The compressor used for this system has an output of 1600 SCFM (45.3 SCMM). The U.S. Army Corps of Engineers (USACE 2006) recommends that the maximum nozzle diameter be such that the total area of the nozzles is less than 25% of the cross-sectional area of the manifold pipe. The installed nozzle diameter of 0.236 in. (6 mm) does not satisfy this requirement. The maximum nozzle diameter, d, for a manifold design can be determined from

$$d = D\sqrt{\frac{0.25}{n}} \tag{3}$$

where *D* is the manifold pipe ID and *n* is the number of nozzles in the manifold. For the calculations, I reduced the nozzle diameter to 0.22 in. (5.6 mm) to satisfy this area requirement that is enforced in BUB300.

Appendix A provides the results of the bubbler performance calculations, and Figure 6 and Table 1 summarize this. I ran two cases: one for new galvanized pipe and one with a roughness associated with "old" galvanized pipe. The results show that the average flow through the nozzles for new pipe is about 9.3 CFM (0.26 CMM) and varies from 10.5 CFM (0.30 CMM) at the west wall to 8.8 CFM (0.25 CMM) at the east wall.

Figure 6. A comparison of the computed flow output along the length of the existing air-curtain manifold at Lock 8.

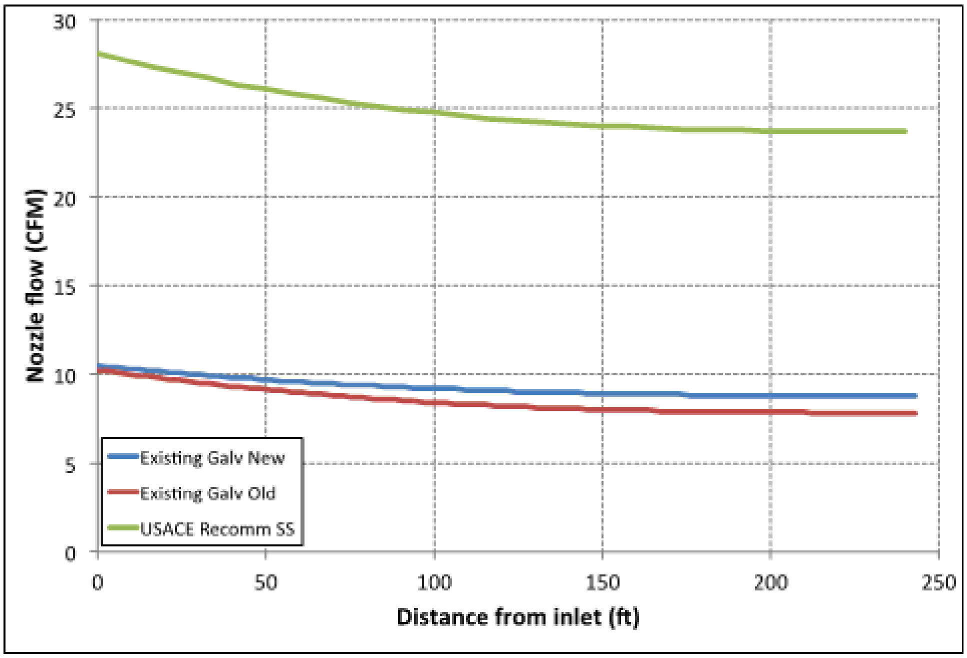


Table 1. A summary of calculations for the existing bubbler screen located at the bullnose above Lock 8. The first two rows are for the existing bubbler design. The last row compares the existing design to the USACE (2006) recommended design for nozzle spacing and size. All of the below calculations, except where noted, assume a maximum compressor output of 1600 SCFM (i.e., flow at standard conditions).

Air Curtain Condition	Spacing (ft) / Nozzle dia. (in.)	Total flow at depth (CFM)	Average nozzle flow (CFM)	Coefficient of Uniformity, *CU*
Existing Air Curtain, 243 ft (74 m)				
New galv. pipe	3 / 0.22	750	9.3	0.18
Old galv. pipe	3 / 0.22	688	8.5	0.28
USACE (2006) recommended design, 243 ft (74 m)				
1600 SCFM (45.3 SCMM), new SS[1]	8 / 0.36	748	25	0.18
2200 SCFM, (62.3 SCMM) new SS	8 / 0.36	1000	33	0.14
Air-Curtain Rehab Design (30 September 2015), 265 ft (80.8 m)				
USACE (2006), 2400 SCFM (68 SCMM) new SS	8 / 0.35	1120	33	0.15

[1] Stainless steel

By comparing the total discharge, Q, for the old and new design, the total flow reduction in the old pipe is 61.5 CFM (1.7 CMM). Therefore the effectiveness of the bubbler is reduced by about 8% just due to aging of the pipe. I also compute CU, a coefficient of uniformity,

$$CU = (Q_{max} - Q_{min}) \ / \ Q_{ave}, \tag{4}$$

that gives an indication of the degree of variation in the flow across the manifold in comparison to the average nozzle discharge. The closer CU is to zero, the more uniform the flow. Table 1 also includes CU information for the new and old case.

Table 1 shows that there is a depreciable reduction in flow uniformity in the older pipe vs. the new pipe; the CU of the old pipe is over 50% higher than that of the new pipe. Therefore, there is clearly a weakening of the flow at the east wall just due to increased roughness of the aged pipe; and that will be further exacerbated by any additional corrosion effects (e.g., blockage or leaks as discussed previously). I further note that because the actual nozzle diameter is 0.236 in. (6 mm) rather than the 0.22 in. (5.6

mm) used in the calculations, the nozzle discharge in the existing bubbler screen is less uniform than what the above calculations estimate.

USACE (2006) recommends 8 ft (2.44 m) spacing, 3/8 in. (9.53 mm) nozzles, and 33 CFM (0.93 CMM) flow out each nozzle. Yet the existing design appears to function properly when new. This is likely because the existing system has a flow of about 10 CFM (0.3 CMM) at each nozzle, and three nozzles span 9 ft (2.74 m); so over approximately the same span, the outflow is close to what USACE (2006) recommends. For comparison, I have performed a calculation using BUB300 and the recommended design from USACE (2006). Figure 6 and Table 1 include the results of that calculation. Again, because of the number of nozzles in the manifold, the recommended nozzle size of 3/8 in. (9.53 mm) with an 8 ft (2.44 m) spacing gives a cumulative nozzle area greater than 25% of the manifold pipe area. I adjusted the nozzle diameter to 0.36 in. (9.14 mm) to satisfy this requirement (see Table 1).

The USACE (2006) recommended design gives about the same flow uniformity (CU = 0.18) and total discharge at the nozzles. Yet, the target average flow of 33 CFM (USACE 2006) at each nozzle cannot be realized with the current compressor (1600 SCFM, [45.3 SCMM]). To reach the USACE (2006) recommended target flow of 33 CFM (0.93 CMM), the compressor capacity would need to be increased to 2200 SCFM (62.3 SCMM); Table 1 also shows this case. If a larger compressor were used to provide the target flow, the total nozzle output would increase to 1000 CFM (28.3 CMM) and the uniformity of the flow would improve (CU = 0.14) (Table 1).

The question is, how would the performance of the system improve if a larger compressor were used? The limited data of Hanamoto (1981) and Tuthill and Stockstill (2005) provide some insight into possible performance improvements in the form of increased capacity to hold back ice if a larger compressor were used. Figure 7 shows data from laboratory and field measurements of the near-surface horizontal velocity induced by high-flow bubblers. This figure shows that the average near-surface velocity, V, is weakly dependent on the manifold depth, H, and strongly dependent on the airflow rate, Q. I determined the following expression to describe these trends in the data presented in Figure 7:

$$V(\text{mm/s}) = CQ(\text{SCMM/m})^{0.4223}; C = 351 + 25.47H(\text{m}) \qquad (5)$$

Note, the manifold flow rate in Figure 7 and Equation (5) is given as SCMM/m, the flow normalized by the manifold length. This volumetric flow rate is higher than the output volumetric flow at the nozzle as reported in Table 1, owing to the higher pressure at the depth of the manifold.

The drag force, F_d, exerted by the water on the ice is

$$F_d = \frac{1}{2} C_d \rho V^2 A \qquad (6)$$

where

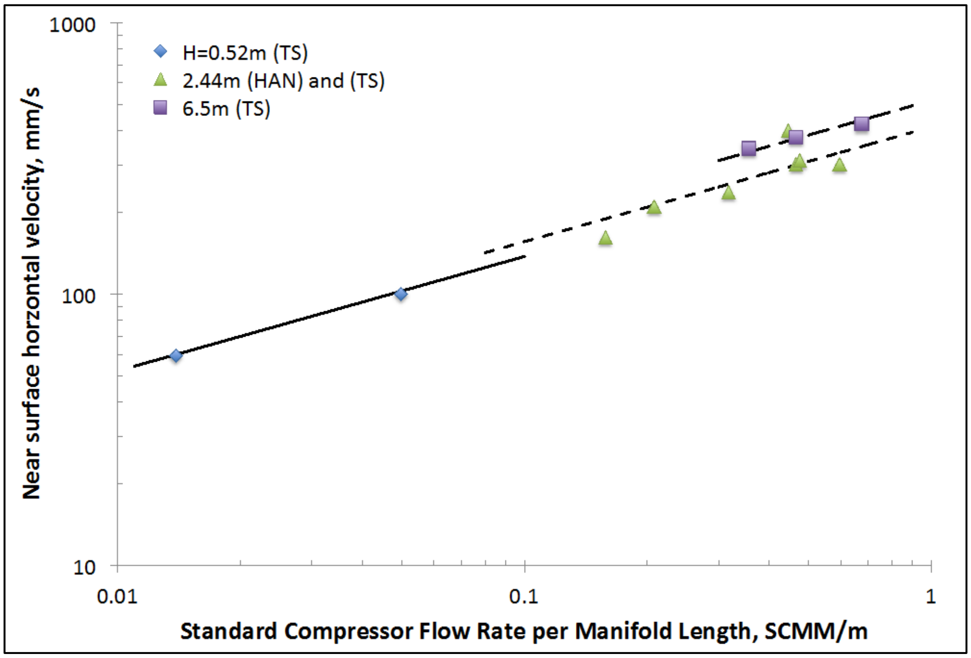
ρ = the water density,
A = the characteristic surface area (e.g., frontal area) between the water and the ice, and
C_d = the drag coefficient determined for the associated A.

We need not know the quantities for all of the terms in Equation (6); all other things being equal, we find from Equation (6) that the drag or resisting force that the bubbler can create is proportional to V^2. Therefore, we can estimate the improved performance of the bubbler screen to hold back ice by using Equation (6) to estimate the increase in surface velocity. From this, the estimated near-surface velocity of the existing bubbler screen (1600 SCFM [45SCMM]) would be 15.5 ft/s (474 mm/s); the revised screen (2200 SCFM [62SCMM]) would have a near-surface velocity of 17.8 ft/s (543 mm/s). The improvement in the screen hold back force would be

$$\frac{F_{d\_rev}}{F_{d\_ex}} = \left(\frac{542\text{mm/s}}{474\text{mm/s}}\right)^2 = 1.31,$$

or a 31% improvement in the ability to hold back ice. It is unclear at this point whether a 30% improvement in the ability of the bubbler to hold back ice would offset the increased fuel and rental costs associated with using a larger compressor. The above calculation is independent of the manifold design (3 ft [0.91 m] or 8 ft [2.4 m] spacing); therefore, adding a larger compressor could be done with the existing design, and the same performance gains should be realized.

Figure 7. The observed near-surface horizontal water velocity induced by high-flow bubblers. The observations were made by Hanamoto (1981) (HAN) and Tuthill and Stockstill (2005) (TS). *H* is the submerged depth of the bubbler manifold. The lines indicate the predicted performance from Equation (5). The manifold flow is in standard cubic meters per minute per meter of manifold length (SCMM/m) (1 CMM = 35.3 CFM).



I now apply this same approach to the bubbler design that will replace the existing system. The new bubbler will span a longer distance (265 ft [80.8 m]) and the manifold will be 264 ft (80.5 m) long. The recommended design is for 8 ft (2.4 m) spacing between nozzles, a total of 34 nozzles. To satisfy uniform flow requirements, the nozzle size will need to be reduced to 0.35 in. (8.9 mm) (i.e., an S drill size). To maintain the recommended average flow of 33 CFM (0.93 CMM) at the nozzles, the compressor capacity would need to be increased to 2400 SCFM (68 SCMM). With this design, the ability of the air curtain to hold back ice would be increased by about 30%.

In addition to the above-recommended design, a check valve should also be added near the bottom of the supply line to prevent backflow of water through the manifold and up the supply pipe where it can potentially freeze and plug or damage the supply line.

3.5 Ice flushing

This is a common procedure used worldwide in locks to clear ice from the lock and the upper approach, and the procedure outlined in SLSMC (2015) is consistent with common practice. According to SLSMC (2015), the low head at Lock 8 allows opening of the lower gates even when the lock chamber is not emptied. This makes the operation more effective as ice is flushed out with the surge of water that flows out of the chamber as the lower miter gates are opened. The only possible problem with this approach is that other locks that use this method have experienced excessive wear on gate components because of the vibration of the gates as the water flows past the partially opened gates. To my knowledge, that is not a problem at Lock 8.

3.6 Bubbler under Bridge 19

The current design has 100 ft (30 m) manifolds running on either lock wall. The nozzle spacing is 3 ft (0.915 m), and the nozzle diameter is 3/16 in. (4.8 mm). A total of 35 nozzles are on each lock wall. The supply and manifold pipes are 1½ in. (31 mm) ID schedule 40 stainless steel.

This system uses a 750 SCFM (21.2 SCMM) compressor. Using BUB300, I estimate that the flow at the nozzles is about 5 CFM (0.14 CMM), a sufficient flow for preventing icing on the lock walls. However, to be effective at scrubbing ice from the side of a vessel, I would expect that the flow may need to be higher. Yet, based on eyewitness accounts, these bubblers are effective at removing at least a portion of the ice carried alongside a vessel.

It appears that there is no check valve in this system. This should be a considered addition when work is done on this system. Also, to satisfy Equation (3), the nozzle size should be 0.316 in. (8.0 mm) (a number 29 drill size). Therefore, in future revisions, I also recommend reducing the nozzle diameter to 0.316 in. (8.0 mm) to provide more uniform flow out of the nozzles along the manifold length. If a bubbler system is installed under Bridge 19A, these recommended changes apply to that location, also.

4 Future Options

The following are some possible options that may improve the control of ice at Lock 8:

1. Install a secondary air curtain downstream of the one currently at the bullnose.
2. Install check valves on all bubbler systems that are permanently mounted in the WSC.
3. Consider replacing with a manifold bubbler system the blaster bubblers or removable point-source bubblers that are used to clear the gate recesses of ice.
4. Use a water cannon to move ice in and around the lock.
5. Use methods to further reduce the amount of ice passing through the breakwater.
6. Divert ice down the weir channel to reduce the amount of ice that gets into the upper lock approach and into the lock.

A discussion of the practicality and design considerations for each of these options follows. Further work is required to flesh out the design details for many of the options considered.

4.1 Secondary air curtain

Using a secondary air curtain could help to reduce the amount of ice entering the lock chamber. If the hull is not fully cleared of ice after passing through the existing bubbler screen, this second screen could be turned on to help clear the hull of additional ice. Conceptually, the second screen would be located at least one ship length downstream of the existing screen. Lock personnel could monitor the ice as the vessel passes through the first air curtain (i.e., by live video camera mounted near the bullnose with a monitor at the lock house) and activate the second air curtain if needed. Ice flushed off the sides of the vessel by this second air curtain could be held between the two curtains while vessel is locked. After the vessel is locked, the second curtain could be turned off so the ice can be drawn into the lock and be flushed through the lock using standard ice flushing procedures.

This approach is consistent with the use of a high-flow deflector (upper approach) and a high-flow screen (just before gates) at locks on the Illinois and Mississippi waterways in the United States as shown in Figure 8. In addition to helping to hold back ice from entering the gate, the screen bubbler in Figure 8 is also used to open an area in the floating ice to provide a place for the ice in the gate recesses to go when flushing the recesses. Locating a screen further above the lock gates in the upper approach may be fine for Lock 8 as the need to use the screen in assisting recess flushing appears not to be an issue at this site. Figure 9 provides a sketch of the possible placement of a secondary air curtain. The distance downstream from the bullnose is sufficient for a vessel to fit between the two air curtains.

Figure 8. The typical location of bubblers at locks on the Illinois and Mississippi waterways (USACE 2006).

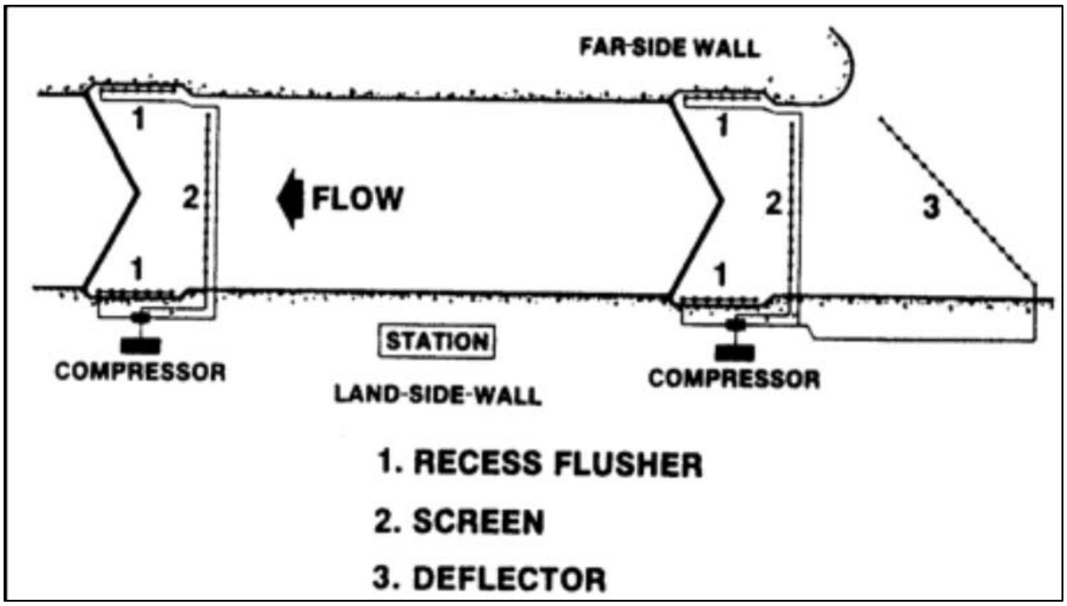
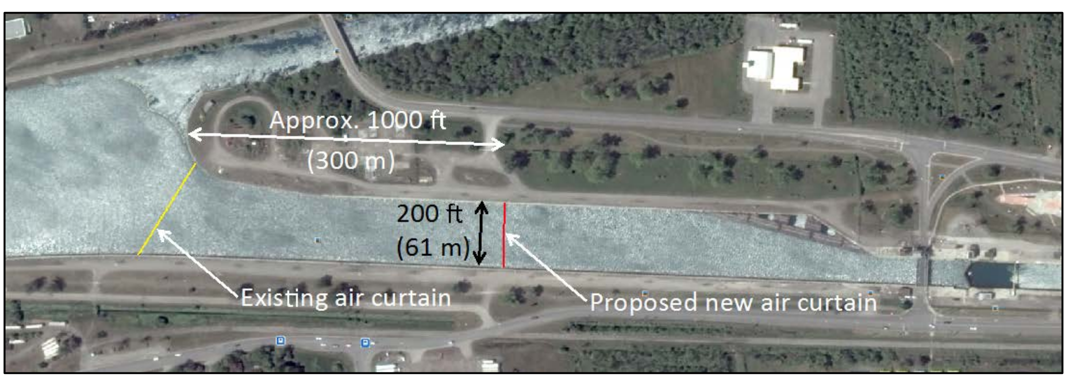


Figure 9. The layout of a new secondary air curtain in the upper approach of Lock 8, Port Colborne, ON.



The design for this secondary air curtain is as follows. I assume a 40 ft (12.2 m) long supply line for this application, similar to what is used at the bullnose; the width of the upper approach is 200 ft (61 m). To provide even spacing of the nozzles, I set the manifold length to 192 ft (58.5 m). The supply and manifold will also be 4 in. (10.2 cm) in diameter as is the case for the existing air curtain. Assuming continued use of a 1600 SCFM compressor to power such a secondary bubbler and USACE (2006) recommended nozzle spacing of 8 ft (2.4 m) and size of 3/8 in. (9.53 mm), the recommended average nozzle outflow of 33 CFM cannot be achieved. To get the desired nozzle outflow, the compressor size needs to be increased to 1800 SCFM (51 SCMM) as indicated in Table 2. Owing to the shorter length of the manifold on this air curtain, the nozzle size can be 3/8 in. (9.53 mm) and still satisfy Equation (3); therefore, I recommend using that size nozzle for this bubbler.

Table 2. The performance summary for a secondary air screen for Lock 8. The recommended nozzle size is 3/8 in. (9.53 mm) spaced 8 ft (2.4 m). The total length of the manifold is 192 ft (58.5 m).

Compressor Output, SCFM (SCMM)	Average Nozzle Flow, CFM (CMM)	Coefficient of Uniformity, *CU*
1600 (45.3)	29.8 (0.844)	0.11
1800 (51.0)	33.9 (0.960)	0.11

4.2 Check valves on bubblers

To ensure more reliable use of the bubblers during winter months, USACE (2006) recommends that intermittently used bubblers have a check valve below the waterline to prevent water returning up the manifold and then freezing inside the pipe at the waterline. The check valve keeps air in the vertical bubbler supply line all the way to the manifold. Though this is not necessary in bubbler lines that are used continuously (e.g., the current air curtain at the bullnose and the bubblers under Bridge 19), inclusion of check valves will prevent freeze-up if these systems need to be shut down during the winter months.

A review of the drawings for the air curtain (Drawing C-8404-1 [Transport Canada 1980]) and for the bubblers under Bridge 19 (Drawing 8424-92 [SLSMC 2012]) shows that check valves are not installed in the vertical rise in the supply line. I recommend that when these bubbler systems are replaced (e.g., January 2016 for the air curtain), a spring check valve be added in the supply line near the bottom elbow (just above the lock floor or river bed) to prevent freezing of the bubbler supply line. Also, if new bubblers are installed elsewhere at the lock, I recommend including check valves in the design. The removable point-source bubblers that use a flexible hose may not benefit from having a check valve as these are removed from the water when not in use. In this case I would recommend storing these in a warm place to prevent water freezing in the hose between uses. Also, to prevent accidental freezing of the lines, these flexible lines should be fully drained of water when stored.

4.3 Revision of gate-recess bubblers

Point-source bubblers located in the quoin area are currently used to flush ice from the recess, though it may take longer as the strength of the plume is weaker further from the point source and is less effective at moving ice far from the source. This is particularly a problem with a bubbler that has the orifice permanently mounted in the gate quoin. Use of manifold bubblers that extend the entire length of the gate recess may be more effective than the point-source bubblers currently used to flush ice from the recess. Figure 8 shows the typical arrangement of a manifold bubbler in a gate recess. A manifold bubbler allows a bubbler curtain to wash up the entire gate recess and is efficient at flushing the ice from the recess area. USACE (2006) provides a recommended design for a lock that is 110 ft (33.5 m) wide, typical of the locks on the Mississippi, Illinois, and Ohio waterways. The manifold for recess flushers described in USACE (2006) are 56 ft (17.1 m) long owing to the longer gates needed in those locks. According to Drawing C-8406 (A. W. Robertson and Co. 1933) the gate recesses at Lock 8 appear to be about 48 ft 2.5 in. (14.7 m). The design provided in USACE (2006) therefore needs to be adapted to suit the smaller recess at Lock 8. I have removed the last length of pipe and nozzle from the USACE (2006) recommended design to shorten the manifold length to 46 ft (14.0 m); otherwise, I preserve the USACE (2006) recommended design for application to Lock 8.

USACE (2006) recommends that the nozzles be more closely spaced in the quoin area and spaced further apart as one approaches the end of the recess. By just removing the last pipe section and nozzle (near the gate end), I preserve the same spacing that USACE (2006) recommends for the remainder of the manifold: 4, 4, 4, 6, 8, and 10 ft (1.2, 1.2, 1.2, 1.8, 2.4, 3, and 3 m). The recommended nozzle diameter is 3/8 in. (9.5 mm) with a flow at the nozzles of 30 CFM. To satisfy Equation (3), the manifold pipe diameter needs to be 2½ in. (63.5 mm) ID. The manifold pipe may need to be bent into a sweep on the quoin and open ends to follow the contour of the recess, and the manifold will need to be mounted between the fendering. The design calculations assume the submergence depth at 30 ft (9.1 m); the actual depth the recess bubbler is mounted may differ from that to be able to position the bubbler between the fenders (e.g., the blast bubbler outlets are mounted at a depth around 33 and 35 ft [10 and 10.7 m]). Furthermore, adjustments to the manifold length and nozzle spacing may be needed to accommodate details of the recess that are not shown in Drawing C-8406 (A. W. Robertson and Co. 1933).

The minimum compressor capacity needs to be 500 SCFM (14.2 SCMM), rather than the 185 SCFM (5.2 SCMM) currently used for the blaster and point-source bubblers that are used to flush the gate recesses. For this design, $CU = 0.03$. For the side the compressor is on (near side), the supply line is assumed to be 40 ft (12.2 m). For the far recess, the supply line is approximately 120 ft (36.6 m). The diameter of the supply line is assumed to be the same as the manifold: 2½ in. (63.5 mm) ID.

4.4 Water cannons

Deck-mounted water cannons have been used off the coast of Newfoundland to deflect small icebergs away from oil platforms (Warbanski and Banke 1987). Tuthill (2000) demonstrated in model studies that water cannons may be used to free up ice above miter gates and to break up jams of ice in lock approaches. However, Tuthill (2000) showed that for both of these situations, use of point-source bubblers was more effective. Still, as an interim solution, water cannons can be readily installed on the top of a lock wall while installation of fixed point-source bubblers will require dewatering the lock and would need to be scheduled for when the lock is not in use (i.e., during the winter). However, use of removable point-source bubblers may be just as effective as an interim solution, provided the bubbler location can be reached from the lock wall or miter gate.

In addition to moving ice, water cannons can be effective at melting ice if warm water is available. As such, this may be a reasonable alternative to bubblers or mechanical means for removing ice built up on lock walls. Warm water can be drawn from the bottom of the lock and sprayed against the walls with a cannon. Yet, it would be important to control the flow so that spray from the cannons does not produce a bigger problem by icing walkways and railings.

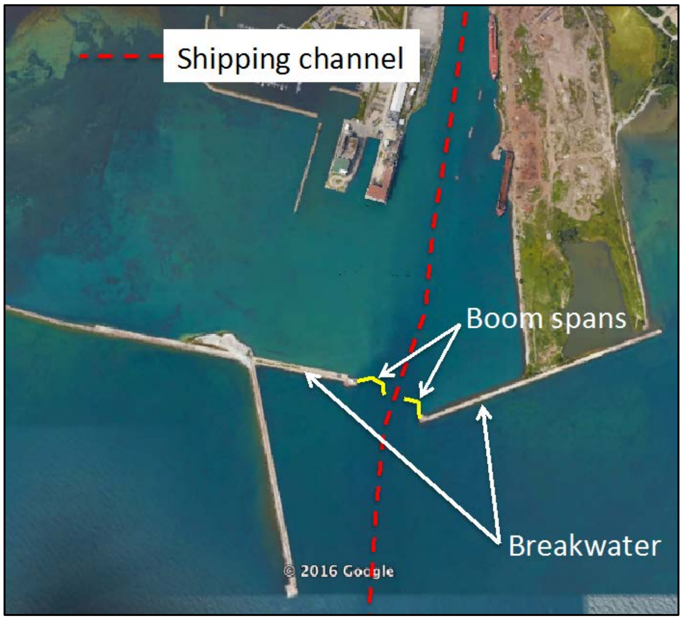
4.5 Reduce the amount of ice passing through the breakwater

Partial closing of the current passage in the breakwater at the shipping channel can further limit the movement of ice from Lake Erie into the shipping channel above Lock 8. The opening in the breakwater is about 614 ft (187 m). Because the vessels are 78 ft (23.8 m) wide, the opening is over 7 times the vessel width. It may be possible to reduce the width of this opening during winter operations while still leaving a gap for shipping traffic. Some possible methods include placing ice booms across the opening or using vessels to move across the gap to close it off while there is no traffic passing through.

The length of a typical vessel using the shipping channel is 730 ft (223 m). Therefore, a vessel positioned across this opening is long enough to close it off. It may be possible to work with the shipping industry to have vessels temporarily position themselves across this opening to block ice for vessels that are passing through the lock (either northbound or southbound). This is not unlike measures taken at some locks to use vessels or barges to block upstream ice from moving into the lock while a second vessel is entering the lock, yet care would need to be taken to ensure that the vessel would not be damaged. For example, when winds are coming from off Lake Erie, the vessel should be positioned within the breakwater so that if the wind was too strong, it would push the vessel away from the breakwater. If the winds are from the other direction, the ice would be pushed away from this opening; and there may be no need to block the opening. Further work is required to determine conditions that are favorable for using this method and how practical such an approach might be. In any event, this should be considered as an expedient measure; and more permanent solutions should be pursued if such an approach proves effective.

A more long-term solution may be to place a boom across the opening as depicted in Figure 10 with an opening in the boom large enough to allow two vessels to pass in opposite directions unhindered. The specific opening size needs to be determined though one might expect that it could be small enough to cut the opening in half. A boom may help stabilize the ice cover in the vicinity of the breakwater and cut down on the amount of ice carried into the WSC by reducing the size of the entrance during winter months. These boom spans could be removed during the summer.

Figure 10. A sketch of the possible geometry of boom spans that allow partial closure of the opening in the breakwater between Lake Erie and the entrance to Welland Ship Canal.



Daly and Weiser (1981) reviewed information on ice passage through a boom opening at Little Rapids Cut on the St. Mary's River. For a boom opening of 250 ft (72 m), there was typically very little ice movement through the opening as vessels passed. Furthermore, owing to ice arching across the boom opening, the ice was stabilized; and little ice passed through the opening when ship traffic was not present. This may provide an indication that an opening on the order of 250 ft (72 m) may work well to limit ice passage from Lake Erie into the WSC. However, this prior work does not consider the effects of onshore winds over Lake Erie and how that may affect ice passage at this site. Therefore, before implementing this approach, I recommend further work to understand the performance of an ice boom across the breakwater opening.

Based on bathymetry data provided by SLSMC and information on Lake Erie water levels, the minimum water depth here appears to be about 34–35 ft (10.4–10.7 m). It may be possible to place a "sink and float" ice boom (Tuthill 1995) across this opening and have part of the boom submerged to allow ship traffic to pass through and then close the gap in the boom while there is no traffic. Further work is needed to explore the details of such a submersible boom system and to determine if it can fit in the 4–5 ft (1.2–1.5 m) of clearance below the shipping channel. Alternately, a tug may be used to swing a boom span out of the opening to allow traffic to pass and then bring the span back into place to close the gap and to limit ice flow. All of these options (boom design and other methods for closing off the breakwater) need to be further developed to determine feasibility.

4.6 Divert ice down the weir channel

Another method that may reduce ice above the bullnose is to divert ice down the weir channel (the left channel in Figure 11). The ice could be allowed to trickle into the channel, reducing the amount of ice above the bubbler screen. The approximate water depth at the mouth of the weir channel is around 17 ft (5.2 m); and at the weir it is 20 ft (6 m) or more, which is sufficient to let ice pass without grounding out on the bed of the channel. Further information is needed to determine if the flow depth in the channel between these points is sufficient to prevent grounding out at any location in the channel.

Figure 11. The upper approach (*right*) to Lock 8. The weir channel is on the *left*. The boom in front of the weir channel prevents ice and debris from passing down the channel.

The volume of ice that is let into the weir channel needs to be low so that it does not jam in the channel but can pass through the channel and weir gates unimpeded. It may be possible to pass the ice through the taintor valves in the weir as follows. Most of the valves would need to be fully closed with the bulk of the flow passing through one or two that are wide open. Based on flow data in the weir channel during the winter months of 2014–15 (December–May), the average water velocity, V, in the channel is approximately 1.7–2.4 ft/s (0.52–0.73 m/s); the range of Froude number ($Fr = V/\sqrt{gD}$; g is the gravitational constant, and D is the water depth) for the flow is 0.06–0.09. These velocities and Froude numbers are in the range required to keep the floes from under turning as they collide with a stationary object ($V < 0.6–0.8$ m/s, $Fr < 0.08–0.12$ [Foltyn and Tuthill 1996]). Therefore, even at the higher flows, it is unlikely that the ice floes will flip and readily be pulled through the valve opening as they reach the structure. Yet, the suction created by gates open at the weir may draw floes through. The force per unit area of the floe, F/A_f (or suction pressure, p) needed to submerge a floe enough to possibly draw it through the valve opening can be estimated by

$$p = \frac{F}{A_f} = (0.1t)\rho_w g \quad (7)$$

where t is the thickness of the ice and the product $0.1t$ is the amount of ice that is floating above the waterline. Using Equation (7), we see that for an 18 in. (46 cm) thick ice floe, the suction needed to draw it under is about 0.065 psi (0.4 kPa).

To explore the possibility that ice can be drawn through the valve opening, we can estimate the available suction through the weir by applying Bernoulli's principle:

$$\Delta p = \rho\left(g\Delta H + \frac{1}{2}\left[V_{surface}^2 - V_{throat}^2\right]\right) \quad (8)$$

The amount of negative pressure (i.e., suction), Δp, between the water surface and the throat of the valve opening is estimated using Equation (8) and provides an indication of the force available to pull floes through the valve opening; ΔH is the difference in elevation between the water surface and the top of the valve opening and varies from about 5.8 to 9.3 ft (1.8 to 2.8m). Equation (8) shows that there is a balance between the increase in pressure created by the hydrostatic head (change in water depth) and the drop in pressure due to the flow acceleration through the throat of the valve. To generate enough velocity to create a suction (negative pressure), the flow can be directed through only one or two valves; otherwise the flow area is too large, and there is no net suction created. Table 3 provides a summary of the suction available (negative values) depending on the number of gates open and the water depth in the channel just upstream of the weir. This shows that generally there is very weak suction with two gates open and that it is highly dependent on the water depth as to whether enough suction (less than −0.065 psi [−0.4kPa]) is generated at all to draw floes through the valve opening. Of the 4 months shown in Table 3, only two of them have average flows high enough to create the needed suction to draw ice through the openings when two valves are open.

Table 3. Estimates of the suction available to pull ice through the weir valves. Suction sufficient to draw an 18 in. (46 cm) thick ice floe under water is indicated by *green* negative values.

Month	Monthly Average Flow in Weir Channel, CFS (CMS)	Pressure Difference, psi (kPa) (Negative Pressure Is Suction)			
		Two Valves Open		One Valve Open	
		Water Depth, ft (m)		Water Depth, ft (m)	
		23 (7.1)	20 (6.0)	23 (7.1)	20 (6.0)
Dec. 2014	9040 (256)	0.9 (6.3)	−0.6 (−4.1)	−8.5 (−59)	−9.9 (−69)
Mar. 2015	7800 (221)	1.7 (12)	0.2 (1.4)	−5.3 (−36)	−6.7 (−47)
Apr. 2015	8190 (232)	1.4 (10)	−0.02 (−0.2)	−6.2 (−43)	−7.1 (−53)
May. 2015	9250 (262)	0.8 (5.3)	−0.7 (−5.1)	−9.1 (−63)	−11 (−73)

The most reliable way to ensure there will be suction to draw the ice through the openings is to have only one valve open. However, it appears that the valve machinery (Drawing 12033-18 [SLSMC 2001]) is configured to operate two valves in tandem. Therefore, for this method to work reliably, the machinery for one set of valves would need to be modified to allow operation of only one valve at a time. Additionally, it is likely that any valves that will be used for passing ice will need to be modified by adding a skin plate on the underside of the truss work to prevent the ice that is being flushed through from getting caught in the trusses.

If this approach is considered, ice could be diverted down the channel by modifying a couple of the pontoons in the boom to allow them to be filled with water so that they will partially sink to let ice pass. Yet the pontoons would be equipped with an air hose tied to a compressor on shore that would allow pushing the water out of the pontoons so they could be refloated to stop ice from diverting into the weir channel. Because the openings in the weir are only 15 ft (4.6 m) wide, I recommended limiting the number of pontoons that can be partially submerged to two. The pontoons are about 17 ft (5.2 m) long (as measured using Google Earth); partial sinking of one or two pontoons would help control the size of ice that is passing through the boom to around 15 ft (4.6 m) or less as it is critical to keep the ice-floe size that is diverted down the weir channel smaller than the weir openings. Partially filling two adjacent pontoons with water would cause these to dip under water where the pontoons meet, allowing small pieces of ice to pass. The piece size can be controlled by the degree of submergence of the two pontoons. Some trial and error will likely be needed to determine how much submergence is effective and whether only one pontoon needs to be submerged to control the flow of ice and piece size. Further work needs to be done to determine where in the boom structure these submersible pontoons should be located, though I would expect that somewhere near the middle of the boom would work well as there is enough room between the shore and bullnose to allow unimpeded movement of the ice once it passes through the boom.

5 Summary and Recommendations

In this effort, I reviewed the current practices used at Lock 8 on the WSC to control ice and to prevent vessels from becoming jammed in the lock. Current methods include monitoring weather conditions, using ice forecasting methods to determine when to implement ice-control measures, using bubbler screens or air curtains to reduce the amount of ice entering the lock, using bubblers and mechanical methods to remove ice from lock walls and approaches, and flushing ice from miter gate recesses and the lock chamber. Also, the presence of a breakwater between Lake Erie and the WSC helps to reduce ice entering the shipping channel and reaching the lock.

Most of these methods appear to be effective. However, a review of the performance of the blaster bubblers used to clear ice from the miter gate recesses shows that this may not be as effective as herding the ice out of the recess with a removable point-source bubbler. Also, I recommend a design for a manifold recess bubbler (Section 4.3) that may be much more effective and reliable for clearing the gate recess of ice than either the blaster bubbler or the removable point-source bubbler.

A review of the existing and planned replacement air curtain (Table 1) revealed that the existing nozzles are too large to provide uniform airflow across the length of the air-curtain manifold. From this review and based on the design guidelines of USACE (2006), I recommend that the replacement air curtain use nozzles that are 0.35 in. (8.9 mm) in diameter (S drill size) with a spacing of 8 ft (2.4 m). The new air curtain would require a compressor capacity of 2400 SCFM (68 SCMM). I estimate the new curtain would have a 30% higher capacity to hold back ice than the existing air curtain.

Also, reducing the nozzle diameter to 0.316 in. (8.0 mm, or a number 29 drill) would improve uniformity in the airflow rate across length of the bubbler manifold for the bubblers under Bridge 19. I recommend that when this bubbler is rehabbed, the existing nozzles be replaced with this smaller nozzle size. These recommendations should also be followed if a new bubbler system is installed under Bridge 19A.

Furthermore, I recommend several additions or revisions to the existing ice-control measures. First, to reduce the likelihood of the bubbler supply lines becoming frozen during the winter months I recommend installing check valves in the supply line as discussed in Section 4.2.

Addition of a second air curtain downstream of the existing air curtain may help to reduce the ice entering the lock and thereby reduce the chances of a vessel becoming jammed in the lock chamber. As detailed in Section 4.1, this second air curtain would be operated intermittently to hold ice that passed through the first air curtain in the lock approach until the vessel has been locked. Then the ice held by this secondary curtain could be released and flushed through the lock by using existing ice lockage procedures.

This report also discusses the possible use of water cannons to move ice in and around the lock. This may be effective as an interim solution to move ice from some critical areas where bubblers are not installed. However, Tuthill (2000) demonstrated that point-source bubblers are more effective at moving ice and may be a better long-term solution.

Other options that may help to reduce ice in the upper approach include reducing the ice flow through the existing breakwater opening as discussed in Section 4.5 and diverting ice around the lock by passing it through the weir channel and weir structure (Section 4.6). Though the preliminary analysis done in the present effort shows that both of these approaches may be feasible, further work is required to refine the methods and structural design needed to implement these concepts.

References

A. W. Robertson and Co. 1933. Drawing C-8406. 3 December. St. Catharines, ON: A. W. Robertson and Co. LTD.

Daly, S. F., and J. R. Weiser. 1981. Modeling Hydrologic Impacts of Winter Navigation. In *Proceedings of Water Forum '81, 10–14 August, San Francisco, CA*, 2:1073–1080. New York: American Society of Civil Engineers.

Foltyn, E. P., and A. M. Tuthill. 1996. *Design of Ice Booms*. Cold Regions Technical Digest 96-1. Hanover, NH: Cold Regions Research and Engineering Laboratory.

Hanamoto, B. 1981. Ice Control at Navigation Locks. In *Proceedings of Water Forum '81, 10–14 August, San Francisco, CA*, 2:1073–1080. New York: American Society of Civil Engineers.

Kobus, H. E. 1968. Analysis of the Flow Induced by Air-Bubbler Systems. In *Proceedings of Eleventh Conference on Coastal Engineering, September, London, England*, 1:1016–1031. New York: American Society of Civil Engineers.

SLSMC (St. Lawrence Seaway Management Corporation). 2001. Drawing 12033-18. 26 April. Cornwall, ON: St. Lawrence Seaway Management Corporation.

———. 2012. Drawing 8424-92. 18 June. Cornwall, ON: St. Lawrence Seaway Management Corporation.

———. 2015. *Lock Operations Manual*. Cornwall, ON: St. Lawrence Seaway Management Corporation.

Transport Canada. 1980a. Drawing C-8404-1. 17 September. Cornwall, ON: The Seaway, Transport Canada.

———. 1980b. Drawing C-8404-2. 17 September. Cornwall, ON: The Seaway, Transport Canada.

Tuthill, A. M. 1995. *Structural Ice Control: Review of Existing Methods*. Special Report 95-18. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory.

———. 2000. A Physical Model of Ice Passage at the Soo Locks. *Canadian Journal of Civil Engineering* 27:1207–1216.

Tuthill, A. M., and R. L. Stockstill. 2005. Field and Laboratory Validation of High-flow Air Bubbler Mechanics. *Journal of Cold Regions Engineering* 19 (3): 85–99.

USACE (U.S. Army Corps of Engineers). 2006. *Ice Engineering*. EM 1110-2-1612. Washington, DC: U.S. Army Corps of Engineers.

Warbanski, G., and E. Banke. 1987. *Evaluation of a Modified Water Cannon System to Control Small Iceberg Masses*. Environmental Studies Research Funds Report No. 081. Ottawa, ON: Environmental Studies Research Funds.

Appendix A: Air Curtain Calculations

A.1 Existing air curtain with new galvanized pipe

```
                         PROJECT Lock 8 existing bubbler screen
               TYPE OF SYSTEM: Deflector screen

                              INPUT PARAMETERS

** SUPPLY PIPE PARAMETERS

   TOTAL LENGTH:            40.0 ft
   DIAMETER:                 4.0 in

** DIFFUSER LINE PARAMETERS

   NUMBER OF ORIFICES:         81
   ORIFICE DIAMETER:         0.220 in
   DISCHARGE COEFFICIENT:    1.000
   TOTAL LENGTH:             243.0 ft

PIPE MATERIAL: New Galvanized Steel of ROUGHNESS K= 0.001 in

** COMPRESSOR RATINGS
   RATED COMPRESSOR PRESSURE:     22 psi
   RATED COMPRESSOR DISCHARGE:  1600 CFM at ATMOSPHERIC PRESSURE

   DEPTH OF SUBMERGENCE:          30 ft
AIR DENSITY AT RATED PRESSURE: 0.206 lbm/ft^3

AIR FLOW THROUGH PIPES IS ISOTHERMAL @ 0oC
AIR EXPANSION AT NOZZLES IS ADIABATIC

                      CALCULATED SYSTEM PERFORMANCE

** DIFFUSER: PRESSURE AND FLOW DISTRIBUTION
```

LOCATION ft	PRESS. DROP psi	Pin-Pout psi	ORIFICE DISCHARGE (CFM) at 22 psi	at Pdepth	at Patm
0.0		7.8	8.5	10.5	21.6
3.0	0.1	7.8	8.4	10.4	21.4
6.1	0.1	7.7	8.4	10.4	21.3
9.1	0.1	7.6	8.3	10.3	21.2
12.1	0.1	7.5	8.3	10.3	21.1
15.2	0.1	7.4	8.2	10.2	20.9
18.2	0.1	7.4	8.2	10.2	20.8
21.3	0.1	7.3	8.1	10.1	20.7
24.3	0.1	7.2	8.1	10.1	20.6
27.3	0.1	7.1	8.1	10.0	20.5
30.4	0.1	7.1	8.0	10.0	20.4
33.4	0.1	7.0	8.0	9.9	20.3
36.4	0.1	6.9	7.9	9.9	20.2
39.5	0.1	6.9	7.9	9.8	20.1
42.5	0.1	6.8	7.9	9.8	20.0
45.6	0.1	6.8	7.8	9.8	19.9
48.6	0.1	6.7	7.8	9.7	19.8
51.6	0.1	6.6	7.8	9.7	19.7
54.7	0.1	6.6	7.7	9.6	19.6
57.7	0.1	6.5	7.7	9.6	19.6
60.8	0.1	6.5	7.7	9.6	19.5
63.8	0.0	6.4	7.6	9.5	19.4
66.8	0.0	6.4	7.6	9.5	19.3
69.9	0.0	6.3	7.6	9.5	19.3
72.9	0.0	6.3	7.5	9.4	19.2
75.9	0.0	6.3	7.5	9.4	19.1
79.0	0.0	6.2	7.5	9.4	19.0
82.0	0.0	6.2	7.5	9.4	19.0
85.1	0.0	6.1	7.4	9.3	18.9
88.1	0.0	6.1	7.4	9.3	18.9
91.1	0.0	6.1	7.4	9.3	18.8
94.2	0.0	6.0	7.4	9.2	18.7
97.2	0.0	6.0	7.3	9.2	18.7
100.2	0.0	6.0	7.3	9.2	18.6
103.3	0.0	5.9	7.3	9.2	18.6

106.3	0.0	5.9	7.3	9.2	18.5
109.4	0.0	5.9	7.3	9.1	18.5
112.4	0.0	5.8	7.2	9.1	18.4
115.4	0.0	5.8	7.2	9.1	18.4
118.5	0.0	5.8	7.2	9.1	18.4
121.5	0.0	5.8	7.2	9.1	18.3
124.5	0.0	5.7	7.2	9.0	18.3
127.6	0.0	5.7	7.2	9.0	18.2
130.6	0.0	5.7	7.1	9.0	18.2
133.7	0.0	5.7	7.1	9.0	18.2
136.7	0.0	5.7	7.1	9.0	18.1
139.7	0.0	5.6	7.1	9.0	18.1
142.8	0.0	5.6	7.1	9.0	18.1
145.8	0.0	5.6	7.1	8.9	18.1
148.8	0.0	5.6	7.1	8.9	18.0
151.9	0.0	5.6	7.1	8.9	18.0
154.9	0.0	5.6	7.1	8.9	18.0
158.0	0.0	5.5	7.1	8.9	18.0
161.0	0.0	5.5	7.0	8.9	17.9
164.0	0.0	5.5	7.0	8.9	17.9
167.1	0.0	5.5	7.0	8.9	17.9
170.1	0.0	5.5	7.0	8.9	17.9
173.1	0.0	5.5	7.0	8.9	17.9
176.2	0.0	5.5	7.0	8.8	17.9
179.2	0.0	5.5	7.0	8.8	17.8
182.3	0.0	5.5	7.0	8.8	17.8
185.3	0.0	5.5	7.0	8.8	17.8
188.3	0.0	5.5	7.0	8.8	17.8
191.4	0.0	5.5	7.0	8.8	17.8
194.4	0.0	5.4	7.0	8.8	17.8
197.4	0.0	5.4	7.0	8.8	17.8
200.5	0.0	5.4	7.0	8.8	17.8
203.5	0.0	5.4	7.0	8.8	17.8
206.6	0.0	5.4	7.0	8.8	17.8
209.6	0.0	5.4	7.0	8.8	17.8
212.6	0.0	5.4	7.0	8.8	17.8
215.7	0.0	5.4	7.0	8.8	17.7
218.7	0.0	5.4	7.0	8.8	17.7
221.7	0.0	5.4	7.0	8.8	17.7
224.8	0.0	5.4	7.0	8.8	17.7
227.8	0.0	5.4	7.0	8.8	17.7
230.9	0.0	5.4	7.0	8.8	17.7
233.9	0.0	5.4	7.0	8.8	17.7
236.9	0.0	5.4	7.0	8.8	17.7
240.0	0.0	5.4	7.0	8.8	17.7
243.0	0.0	5.4	7.0	8.8	17.7

```
TOTAL PRESSURE DROP IN SUPPLY LINE:        1.1 psi
TOTAL PRESSURE DROP IN DIFFUSER:           2.4 psi
TOTAL PRESSURE DROP IN SYSTEM:             3.6 psi

PRESSURE AT DIFFUSER END:                 18.4 psi
HYDROSTATIC PRESSURE:                     13.0 psi
CALCULATED COMPRESSOR DISCHARGE AT ATMOSPHERIC PRESSURE: 1521 CFM
RATED minus CALCULATED DISCHARGE (at ATM Pressure)    79 CFM
```

A.2 Existing air curtain with old galvanized pipe

```
PROJECT Lock 8 existing bubbler screen
                     TYPE OF SYSTEM: Deflector screen

                                 INPUT PARAMETERS

** SUPPLY PIPE PARAMETERS

   TOTAL LENGTH:            40.0 ft
   DIAMETER:                 4.0 in

** DIFFUSER LINE PARAMETERS

   NUMBER OF ORIFICES:         81
   ORIFICE DIAMETER:          0.220 in
   DISCHARGE COEFFICIENT:     1.000
   TOTAL LENGTH:              243.0 ft

PIPE MATERIAL: Old Galvanized Steel of ROUGHNESS K= 0.010 in

** COMPRESSOR RATINGS
   RATED COMPRESSOR PRESSURE:     22 psi
   RATED COMPRESSOR DISCHARGE:  1600 CFM at ATMOSPHERIC PRESSURE

   DEPTH OF SUBMERGENCE:          30 ft
AIR DENSITY AT RATED PRESSURE: 0.206 lbm/ft^3

AIR FLOW THROUGH PIPES IS ISOTHERMAL @ 0oC
AIR EXPANSION AT NOZZLES IS ADIABATIC

                      CALCULATED SYSTEM PERFORMANCE

** DIFFUSER: PRESSURE AND FLOW DISTRIBUTION
```

LOCATION ft	PRESS. DROP psi	Pin-Pout psi	ORIFICE DISCHARGE (CFM) at 22 psi	at Pdepth	at Patm
0.0		7.5	8.2	10.2	21.0
3.0	0.1	7.3	8.2	10.2	20.8
6.1	0.1	7.2	8.1	10.1	20.6
9.1	0.1	7.1	8.0	10.0	20.5
12.1	0.1	7.0	8.0	9.9	20.3
15.2	0.1	6.9	7.9	9.9	20.1
18.2	0.1	6.8	7.8	9.8	20.0
21.3	0.1	6.7	7.8	9.7	19.8
24.3	0.1	6.6	7.7	9.7	19.7
27.3	0.1	6.5	7.7	9.6	19.5
30.4	0.1	6.4	7.6	9.5	19.4
33.4	0.1	6.3	7.6	9.5	19.2
36.4	0.1	6.2	7.5	9.4	19.1
39.5	0.1	6.1	7.4	9.3	19.0
42.5	0.1	6.1	7.4	9.3	18.8
45.6	0.1	6.0	7.3	9.2	18.7
48.6	0.1	5.9	7.3	9.2	18.6
51.6	0.1	5.8	7.2	9.1	18.4
54.7	0.1	5.8	7.2	9.1	18.3
57.7	0.1	5.7	7.1	9.0	18.2
60.8	0.1	5.6	7.1	9.0	18.1
63.8	0.1	5.6	7.1	8.9	18.0
66.8	0.1	5.5	7.0	8.9	17.9
69.9	0.1	5.4	7.0	8.8	17.8
72.9	0.1	5.4	6.9	8.8	17.7
75.9	0.1	5.3	6.9	8.7	17.6
79.0	0.1	5.3	6.9	8.7	17.5
82.0	0.1	5.2	6.8	8.6	17.4
85.1	0.1	5.2	6.8	8.6	17.3
88.1	0.0	5.1	6.8	8.6	17.2
91.1	0.0	5.1	6.7	8.5	17.1
94.2	0.0	5.0	6.7	8.5	17.0
97.2	0.0	5.0	6.7	8.4	17.0
100.2	0.0	4.9	6.6	8.4	16.9
103.3	0.0	4.9	6.6	8.4	16.8
106.3	0.0	4.9	6.6	8.3	16.8
109.4	0.0	4.8	6.6	8.3	16.7
112.4	0.0	4.8	6.5	8.3	16.6
115.4	0.0	4.8	6.5	8.3	16.6
118.5	0.0	4.7	6.5	8.2	16.5

121.5	0.0	4.7	6.5	8.2	16.4
124.5	0.0	4.7	6.4	8.2	16.4
127.6	0.0	4.6	6.4	8.2	16.3
130.6	0.0	4.6	6.4	8.1	16.3
133.7	0.0	4.6	6.4	8.1	16.2
136.7	0.0	4.6	6.4	8.1	16.2
139.7	0.0	4.5	6.3	8.1	16.2
142.8	0.0	4.5	6.3	8.1	16.1
145.8	0.0	4.5	6.3	8.0	16.1
148.8	0.0	4.5	6.3	8.0	16.0
151.9	0.0	4.5	6.3	8.0	16.0
154.9	0.0	4.4	6.3	8.0	16.0
158.0	0.0	4.4	6.3	8.0	15.9
161.0	0.0	4.4	6.3	8.0	15.9
164.0	0.0	4.4	6.2	8.0	15.9
167.1	0.0	4.4	6.2	7.9	15.9
170.1	0.0	4.4	6.2	7.9	15.8
173.1	0.0	4.4	6.2	7.9	15.8
176.2	0.0	4.3	6.2	7.9	15.8
179.2	0.0	4.3	6.2	7.9	15.8
182.3	0.0	4.3	6.2	7.9	15.8
185.3	0.0	4.3	6.2	7.9	15.8
188.3	0.0	4.3	6.2	7.9	15.7
191.4	0.0	4.3	6.2	7.9	15.7
194.4	0.0	4.3	6.2	7.9	15.7
197.4	0.0	4.3	6.2	7.9	15.7
200.5	0.0	4.3	6.2	7.9	15.7
203.5	0.0	4.3	6.2	7.9	15.7
206.6	0.0	4.3	6.2	7.9	15.7
209.6	0.0	4.3	6.2	7.9	15.7
212.6	0.0	4.3	6.2	7.8	15.7
215.7	0.0	4.3	6.2	7.8	15.7
218.7	0.0	4.3	6.1	7.8	15.7
221.7	0.0	4.3	6.1	7.8	15.7
224.8	0.0	4.3	6.1	7.8	15.7
227.8	0.0	4.3	6.1	7.8	15.6
230.9	0.0	4.3	6.1	7.8	15.6
233.9	0.0	4.3	6.1	7.8	15.6
236.9	0.0	4.3	6.1	7.8	15.6
240.0	0.0	4.3	6.1	7.8	15.6
243.0	0.0	4.3	6.1	7.8	15.6

```
TOTAL PRESSURE DROP IN SUPPLY LINE:        1.5 psi
TOTAL PRESSURE DROP IN DIFFUSER:           3.2 psi
TOTAL PRESSURE DROP IN SYSTEM:             4.7 psi

PRESSURE AT DIFFUSER END:                 17.3 psi
HYDROSTATIC PRESSURE:                     13.0 psi
CALCULATED COMPRESSOR DISCHARGE AT ATMOSPHERIC PRESSURE: 1385 CFM
RATED minus CALCULATED DISCHARGE (at ATM Pressure)   215 CFM
```

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
May 2016

2. REPORT TYPE
Technical Report/Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Review of Ice-Control Methods at Lock 8, Welland Canal, Port Colborne, Ontario

5a. CONTRACT NUMBER
C-15-CRL-15

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Robert B. Haehnel

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CRREL SR-16-1

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
St. Lawrence Seaway Management Corporation
St. Catharines, Ontario

10. SPONSOR/MONITOR'S ACRONYM(S)
SLSMC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This effort reviews the existing procedures and equipment used at Lock 8 on the Welland Ship Canal, Ontario, Canada, to control ice and to reduce the possibility of ice causing a shipping vessel to get stuck or jammed in the lock chamber. The lock uses several methods, including an air curtain to hold ice above the lock, bubblers and mechanical means to reduce the ice accumulation on the lock walls, and bubblers to flush ice from the gate recesses.

A review of all of these methods shows that mostly they have been effective, though some recommended modifications include reducing the air-curtain and bubblers nozzle size to make the flow across the manifolds more uniform. The only system that the St. Lawrence Seaway Management Corporation might consider replacing entirely is the blaster bubblers, which are unreliable and ineffective.

This report details recommended improvements to ice control at Lock 8, including a secondary air curtain below the existing air curtain, a manifold recess bubbler, and methods to further reduce the quantity of ice passing through the breakwater and bypassing ice down the weir channel. Further work is required to determine feasibility and the final design for each of these recommended changes.

15. SUBJECT TERMS
Bubbler or air curtain
Ice breaking operations
Ice prevention and control
Inland navigation
Locks (Hydraulic engineering)
Port Colborne (Ont.)
Saint Lawrence Seaway
Shipping

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	Unclassified	Unclassified	SAR	50	